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DYNAMIC INCREASE FACTORS FOR STEEL REINFORCING BARS

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ABSTRACT

For reinforced concrete structures subjected to blast effects, response at very high strain rates (up to 1000 s^{-1}) is often sought. At these high strain rates, the reinforcing bars yield stress can increase by 100%, or more, depending on the grade of steel used. The dynamic increase factor (DIF), i.e. the ratio of the dynamic to static value, is normally reported as function of strain rate. Knowledge of the DIF is of significant importance in the design and analysis of structures for explosives safety. DIF curves for both yield and ultimate strengths have been derived and published in manuals by the Tri-Services, the Defense Special Weapons Agency, the Air Force, and the Department of Energy. However, these curves are typically based on limited data, and even on data from steel bars of a different grade.

A literature review of the effects of high strain rates on the properties of steel reinforcing bars (rebars) was conducted. Static and dynamic properties were gathered for bars satisfying ASTM A615, A15, A432, A431, and A706, with yield stresses ranging from 42 to 103 ksi (290 to 710 MPa). The data indicates that the DIF decreases for higher rebar yield stress, and that the DIF is higher for yield stress than for ultimate stress. A simple relationship is proposed that gives the DIF (for both yield and ultimate stress) as a function of strain rate and yield stress.

INTRODUCTION

Various standards and studies have addressed the static and dynamic properties of steel reinforcing bars (rebars) [1-25]. Although some static properties, such as yield and ultimate strengths, are dictated by ASTM standards and therefore known to equal or exceed some minimum values, others are not well defined. Under dynamic loading, the strength properties of rebars are known to increase by up to 60% for strain rates of up to 10 s^{-1}, and up to 100% for strain rates around 225 s^{-1}. This paper presents a literature review of most ASTM grades of steel

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bars used as reinforcement in concrete, and proposes criteria for the dynamic increase factor (DIF) for ASTM A615 Grades 40, 60 and 75 rebars.

RESEARCH SIGNIFICANCE

In the design of reinforced concrete structures, rebar properties do not need to be exactly known. ASTM A615 only requires that the yield stress of a Grade 60 bar needs to exceed 60 ksi (414 MPa). For analysis purposes, e.g. finite element analysis, an actual value of the yield stress is needed to provide a more accurate prediction of structural response.

For structures subjected to blast effects, response at very high strain rates (up to 100 or 1000 s^{-1}) is often sought. At these high strain rates, the yield stress can increase by 100%, or more, depending on the grade of steel used. The dynamic increase factor (DIF), i.e. the ratio of the dynamic to static value, is normally reported as function of strain rate. Knowledge of the DIF is of significant importance in the design and analysis of structures for explosives safety. DIF curves for both yield and ultimate strengths can be found in manuals published by the Tri-Services [7], the Defense Special Weapons Agency [8], the Air Force [9], and the Department of Energy [10]. Most of these curves are based on work by Keenan [11,12], and work carried out at the Naval Civil Engineering Laboratory (NCEL, now the Naval Facilities Engineering Service Center, NFESC) [12,13,14,15,16].

BACKGROUND

Quasi-static properties for steel bars conforming to ASTM A615 are readily available. A typical stress-strain curve for Grade 60 bars is shown in Figure 1. Unfortunately, much of the available data for dynamic properties of steel rebar pertains to rebar types which were precursors of the current ASTM A615, which was established in 1968. Most of the early data was obtained for rebar types no longer used such as ASTM A15 (structural, intermediate and hard grade), A432 (60 ksi or 414 MPa yield stress), and A431 (75 ksi or 517 MPa yield stress). Most of the dynamic data for yield stress was actually obtained for the upper yield stress, shown in Figure 1.

Keenan [11] performed dynamic tests on #6, #7 and #9 rebars with static yield strengths between 40 and 49 ksi (276 and 338 MPa) which followed ASTM A15-58T (Figure 2). These rebars were precursors to the current ASTM A615 Grade 40 bars. For lack of other data, the Air Force manual [9] uses criteria derived from these ASTM A15-58T bars to characterize the dynamic strength properties of ASTM A615 Grade 60 bars (Figure 2). Keenan also gathered data on various other rebar types to characterize the yield strength DIF for ASTM A615 Grade 40 and 60 bars [12]. To provide for some conservatism in design, the Grade 60 curve was chosen as the lower bound of two steel types: an ASTM A15 (hard) steel with an average steel yield stress of 59.7 ksi (412 MPa) and an ASTM A432 steel with an average yield stress of 81.5 ksi (562 MPa) (Figure 3). The curve actually follows the data with the 81.5 ksi (562 MPa) yield stress. This curve is the one used in the Tri-Service design manual [7].

The Tri-Service manual curve and some additional data are shown in Figure 4. It can be observed that the DIF is inversely related to the yield strength: bars with the highest yield stress

(87.1 ksi or 600 MPa) have the lowest DIF, whereas bars with the lowest yield stress (54.7 ksi or 377 MPa) have the highest DIF. This trend appears in all reported data. This trend is also indicated in the DAHS manual which shows less enhancement for Grade 60 than for Grade 40 bars [8]. Figures 2 to 4 are plotted using a linear scale for the DIF and a logarithmic scale for the strain rate. If the same data are plotted on a log-log plot, it appears close to a straight line for all grades and most of the data.

Other rebars fabricated to closely related foreign standards, such as the Canadian CSA-G30 (40 ksi or 276 MPa yield stress) [3] are also of interest.

STATIC PROPERTIES

A typical stress-strain curve for ASTM A615 Grade 60 reinforcing steel is shown in Figure 1. The bar first deforms elastically, reaches an upper yield stress, then a lower yield stress where it remains for a while. Strain hardening then follows, until the ultimate strain and stress are reached. At this point, all locations in the bar still have the same strain. Beyond this point, necking at one location takes place (plastic strain localization), while the rest of the bar unloads elastically. Upon rupture, the zone where the necking occurs is typically used to measure the rupture strain, or the percent elongation. The percent elongation is tied to a gage length (since it is a softening phenomenon) and is only of use for verifying ASTM A615 elongation requirements. In numerical analyses, the ultimate strain (reached at peak, or ultimate stress) is the one which characterizes the bar's energy dissipation potential and should be the value used to characterize bar rupture. The percent elongation, or rupture strain at necking, only occurs at one location and is of not much use numerically when modeling large structures (unless representation of strain softening phenomena is desired, and a gage length determined). The difference between ultimate strain and percent elongation is well defined by some authors [3]. However, the ultimate strain value is often not reported due to the difficulty of determining exactly when the peak stress occurs, to the confusion between ultimate strain and rupture strain, and to the lack of realization of the importance of the ultimate strain in numerical calculations.

Data on static properties for Grade 40, 60 and 75 bars are discussed in the following. Best estimate values are summarized in Table 1.

Grade 40 bars

Mirza and MacGregor report results on about 4000 tests on Grade 40, 50 and 60 bars [4]. For the U.S. made Grade 40 bars (171 tests) the average yield and ultimate strengths were about 48 and 81 ksi (330 and 560 MPa), respectively. For Canadian bars, Allen reports a yield stress between 45.8 and 48.7 ksi (316 and 336 MPa) and ultimate stresses (based on nominal areas) between 76.7 and 80.8 ksi (529 and 557 MPa), depending on the quasi-static strain rate used [3].

Allen also reports an average ultimate strain (at peak stress) of 15.5% and a percent elongation of 22.4% [3]. Ultimate strains are greater for Grade 40 bars than for Grade 60 or 75 bars.

Grade 60 bars

For the U.S. made Grade 60 bars (1356 tests), Mirza and MacGregor [4] report the yield and ultimate strengths, which average about 69 and 109 ksi (475 and 750 MPa), respectively. The average modulus of elasticity was about 29,200 ksi (200 GPa). Note that the Tri-Service manual [7] reports yield and ultimate static strengths to be 66 and 90 ksi (455 and 620 MPa), respectively.

Strains at the onset of strain hardening have been reported from 0.3% to 1.3% [6,19], with an average of about 0.8% for grade 60 bars

ASTM A615 requires a minimum percent elongation of 9% in 8 inches (200 mm) for small bars (#3 to #6), 8% for #7 and #8 bars, and 7% for large bars (#9 to #18). However, for numerical applications, the ultimate strain (at ultimate stress) is of greater interest. Tests results by Cowell on ASTM A432 Grade 60 rebars indicate percent elongations at rupture (i.e. rupture strains at necking) of about 21% but ultimate strains around 12% [15]. Test results by Mo et al. on ASTM A615 Grade 60 rebars showed percent elongations from around 20% for #7 bars to 25% for #3 bars [17]. The same tests showed ultimate strains of about 14% for the #7 bars, and about 18% for the #3 bars. Gran reports ultimate strains around 11% [19]. However, results compiled by Wang et al. indicate percent elongations around 14% and ultimate strains only around 7% [5,6]. Flathau also reports ultimate strains from 7% to 13% [20]. Hence there is significant variability in strain data, from 7% to 18% for the ultimate strain.

Welding of the bars, even when conforming to AWS D1.4-92, will usually result in a small reduction in strength (less than 5%), but a large reduction in ultimate strain (50% or more) [17,18]. Flathau shows ultimate strains of less than 7% for most butt-welded bars [20]. To mitigate the increased brittleness due to welding, ASTM A706 rebars with improved weldability have been recently used. Reference [23] reports a stress-strain curve for such a bar, with a yield stress around 74 ksi (510 MPa), an ultimate stress of 97 ksi (670 MPa), and 13% ultimate strain.

Grade 75 bars

ASTM A615 Grade 75 bars are relatively less used, and less data are available. Flathau reports some static and dynamic data for these bars [20]. The average yield and ultimate strengths were 87 ksi and 119 ksi (600 and 820 MPa), respectively. Ultimate strains were between 6% and 7% (note that even with such small ultimate strains, ASTM A615 percent elongation requirements are easily met).

DYNAMIC PROPERTIES

Strain rates for static coupon tests in compliance with ASTM A370 can vary between 10^{-3} and 10^{-4} s^{-1} between one-half the yield point and the yield point (beyond the yield point, strain rates can vary between about $8x10^{-3}$ and $8x10^{-4}$ s^{-1}). If stress rates are measured and converted to strain rates, the test strain rates allowed by ASTM A370 are actually lower. For Grades 60 and

75, test data show little or no strain rate enhancement for strain rates below 10^{-4} s^{-1}. For Grade 40, Keenan showed only a small effect between 10^{-5} and 10^{-4} s^{-1} [11].

Under high strain rates, both the yield and ultimate stresses of reinforcing bars increase. When the dynamic increase factor (DIF) for yield stress is plotted versus the logarithm of strain rate, the relationship is nonlinear (Figure 3), but it becomes practically linear if a logarithmic scale is used for the DIF as well. A review of loading rate effects on concrete and reinforcing steel [22] indicates that the modulus of elasticity and ultimate strain remain nearly constant, but that other bar properties, such as yield stress and strain, increase with rate. The ultimate stress increase is less significant (up to 5% at high strain rates, according to Keenan [12]).

Most of the available data regarding the yield stress DIF refers to the upper yield stress. Although the upper yield stress may appear less important than the lower yield stress under quasi-static loading (Figure 1), under dynamic loading the lower yield plateau shortens and the upper yield stress appears more significant [15].

Grade 40 bars

Figure 5 shows the yield strength DIFs for Grade 40 or equivalent rebars. It was assumed that the rebars with yield strengths between about 43 and 51 ksi (300 and 350 MPa) would be representative of ASTM Grade 40 bars which have an average yield stress of 48 ksi (330 MPa). These bars correspond to ASTM A15 structural and intermediate grades, and were tested by Keenan [11] and Wood [13] at the Naval Civil Engineering Laboratory. Some data points reported by Crum [24] show that the DIF increases continue for strain rate values of up to 225 s^{-1}.

Grade 60 bars

The Tri-Service manual [7] and DAHS manual [8] recommendations are based on work by Keenan et al. [11,12]. The data used to characterize ASTM A615 Grade 60 bars are based on tests on A432 and A15 hard grade bars by Cowell and Wood [13,15]. The upper yield stress data are shown in Figures 4 and 6. Figure 4 also shows the Tri-Service design DIF curve from Keenan [7,12]. Figure 7 shows that Flathau's data are somewhat different, showing a more significant rate of increase of the DIF with strain rate, in particular beyond 3 s^{-1} (the data points were obtained from Figure 4.4 of [20]). Crum [24] also reports a large DIF value of 1.78 for a 70 ksi (483 MPa) bar, but at a much higher rate of 225 s^{-1} (Figure 7).

Figure 8 shows some limited DIF data for the ultimate strength of Grade 60 rebars. ASTM A15 hard grade and A432 with ultimate stresses of about 98 and 116 ksi (675 and 800 MPa) were available, as well as ASTM A615 #4 and #8 bars with ultimate stresses of 119 and 123 ksi (820 and 848 MPa), respectively. Crum [24] reports somewhat higher DIF values. The measured DIF values for ultimate stress are always smaller than for yield stress.

Grade 75 bars

Figure 9 shows the measured yield stress DIF for ASTM A615 Grade 75 or equivalent rebars. Three rebar types are shown, two corresponding to ASTM A615 and A431, and a third one identified only as a high strength steel.

Strains

As indicated previously, the modulus of elasticity is usually found to remain constant under dynamic loading, hence the yield strain would increase with the yield stress DIF. The ultimate strain (at peak stress) remains constant and the static values indicated earlier apply.

PROPOSED FORMULATION

It was assumed that the DIF data can be approximated by a straight line in a logarithm of the dynamic increase factor (DIF) versus logarithm of strain rate ($\dot{\varepsilon}$) plot. Data from NCEL reports C-90922 [13], R695 [14], R394 [15], N427 [16], Keenan's thesis [11], Gran's data [19], Flathau's data [20], and Crum's data [24] were used, with yield strengths varying from 42 ksi to 103 ksi (290 to 710 MPa). The adopted DIF formulation was, for both yield and ultimate stress:

$$DIF = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha} \tag{1}$$

where for the yield stress, $\alpha = \alpha_{fy}$ was found to be:

$$\alpha_{fy} = 0.074 - 0.040\frac{f_y}{60} \tag{2}$$

and for the ultimate stress, $\alpha = \alpha_{fu}$ was found to be:

$$\alpha_{fu} = 0.019 - 0.009\frac{f_y}{60} \tag{3}$$

and where the strain rate $\dot{\varepsilon}$ is in s^{-1} (1/second), and f_y is the bar yield strength in ksi (if f_y is in MPa, the 60 ksi denominator should be replaced by 414 MPa). Note that in both cases α is a function of f_y. This formulation is valid for bars with yield stresses between 42 and 103 ksi (290 and 710 MPa) and for strain rates between 10^{-4} and 225 s^{-1}.

Figure 5 shows proposed yield stress DIF fits using equations (1) and (2) for various types of Grade 40 or equivalent rebars, each fit depending upon the actual yield stress of each rebar set. It was assumed that rebars with yield stresses between about 43 and 51 ksi (300 and 350 MPa)

would be representative of ASTM Grade 40 bars which have an average yield stress of 48 ksi (330 MPa).

Figure 6 shows fits using the proposed equations of the Grade 60 (or equivalent) data from Figure 4. This data includes ASTM A15 hard grade and ASTM A432 bars with yield stresses between 55 and 87 ksi (380 and 600 MPa), compared to the expected 69 ksi (475 MPa) for a ASTM A615 Grade 60 bar. Figure 7 shows Flathau's data to have a more significant rate of increase of the DIF with strain rate beyond 3 s^{-1}, but this is partly countered by Crum's data [24]. Figure 8 shows the proposed DIF fit for the ultimate stress of Grade 60 bars using equations (1) and (3). This figure supports Keenan's statement that the DIF's for ultimate stress are much lower than the ones for yield stress.

Figure 9 shows the proposed yield stress DIF fits for Grade 75 (or equivalent) bars. Three bar types are shown with yield stresses between 87 and 103 ksi (600 and 710 MPa).

Figure 10 shows the derivation of equation (2). The exponent α_{fy} was found for each test series by using a least squares fit. These values of α_{fy} were then plotted as a function of the yield stress f_y for each test series (Figure 10). It is apparent that assuming that α_{fy} varies linearly with f_y provides a reasonable approximation of the data. A similar procedure was used to determine equation (3), although the scatter was much greater and the data limited.

Finally, Figure 11 show a plot of the proposed formulation for the DIF, i.e. equations (1), (2), and (3), for Grade 40, 60, and 75 bars, assuming mean yield stresses of 48, 69 and 87 ksi (330, 475 and 600 MPa), respectively.

Table 1 summarizes the best estimate values for static properties of ASTM A615 bars, and includes the corresponding α values.

CONCLUSIONS

A literature review was conducted to determine static and dynamic characteristics of steel reinforcing bars. It was found that the dynamic increase factor (DIF) for both yield and ultimate stress is inversely related to the yield stress itself. A formulation was proposed to determine the DIF as a function of strain rate and yield stress which appears to fit all the data properly. This formulation is valid for yield stresses between 42 and 103 ksi (290 and 710 MPa) and for strain rates between 10^{-4} and 225 s^{-1}. This formulation gives the DIF for both yield and ultimate stress.

ACKNOWLEDGMENT

The support over the years of W.A. Keenan, Naval Facilities Engineering Service Center, with this and related explosive safety work is greatly appreciated.

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TABLE 1 - BEST ESTIMATE PROPERTIES OF ASTM A615 BARS.

ASTM A615 GRADE	YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	ULTIMATE STRAIN (%)	YIELD STRESS α_{fy}	ULTIMATE STRESS α_{fu}
40	48	81	15.5	0.042	0.012
60	69	109	12	0.028	0.009
75	87	119	7	0.016	0.006

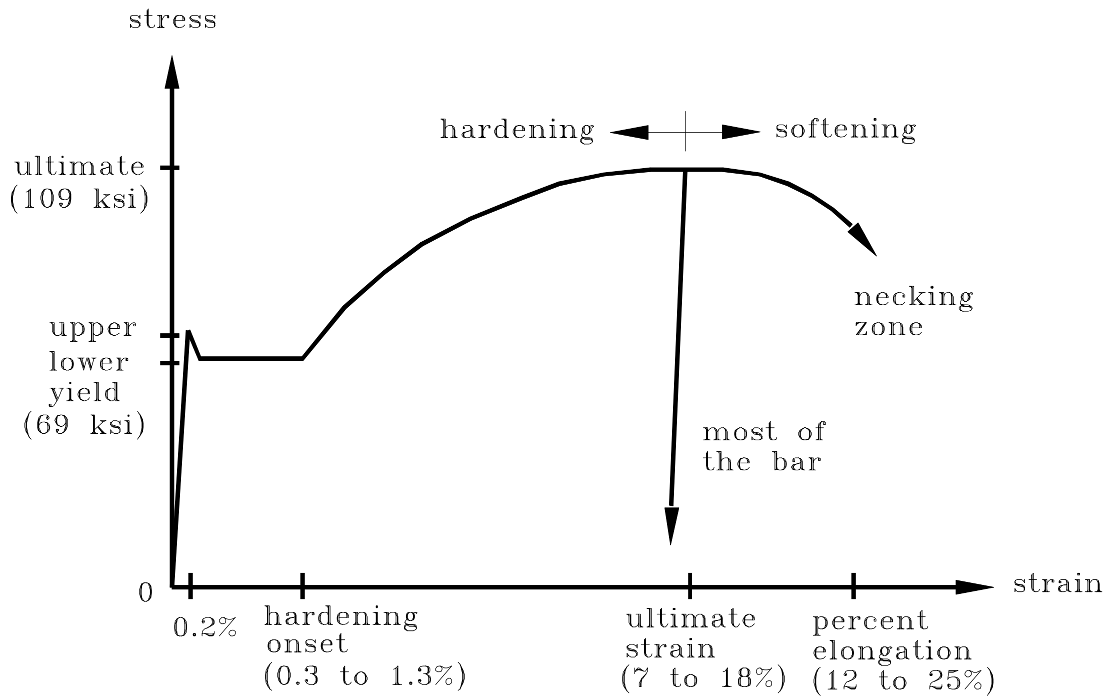

Figure 1. Typical stress-strain curve for ASTM A615 Grade 60 steel.

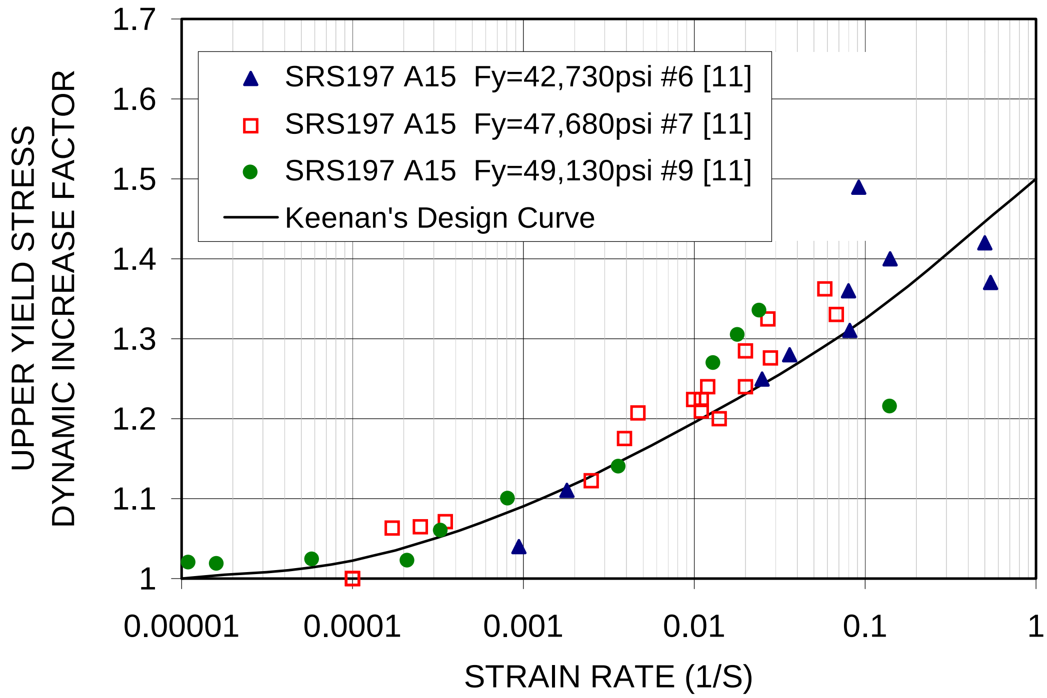

Figure 2. Keenan's data and design curve for ASTM A15 #6, #7 and #9 rebars [9,11].
1 MPa = 145 psi

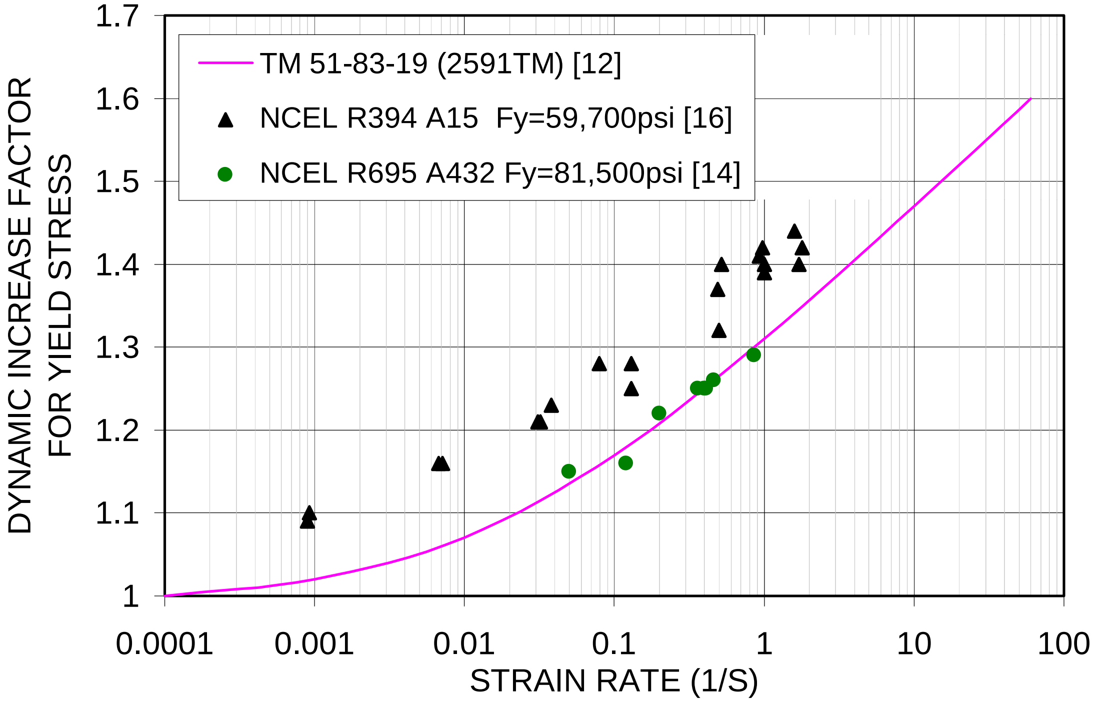

Figure 3. Keenan's design fit for ASTM A432 and A15 data [7,12].
1 MPa = 145 psi

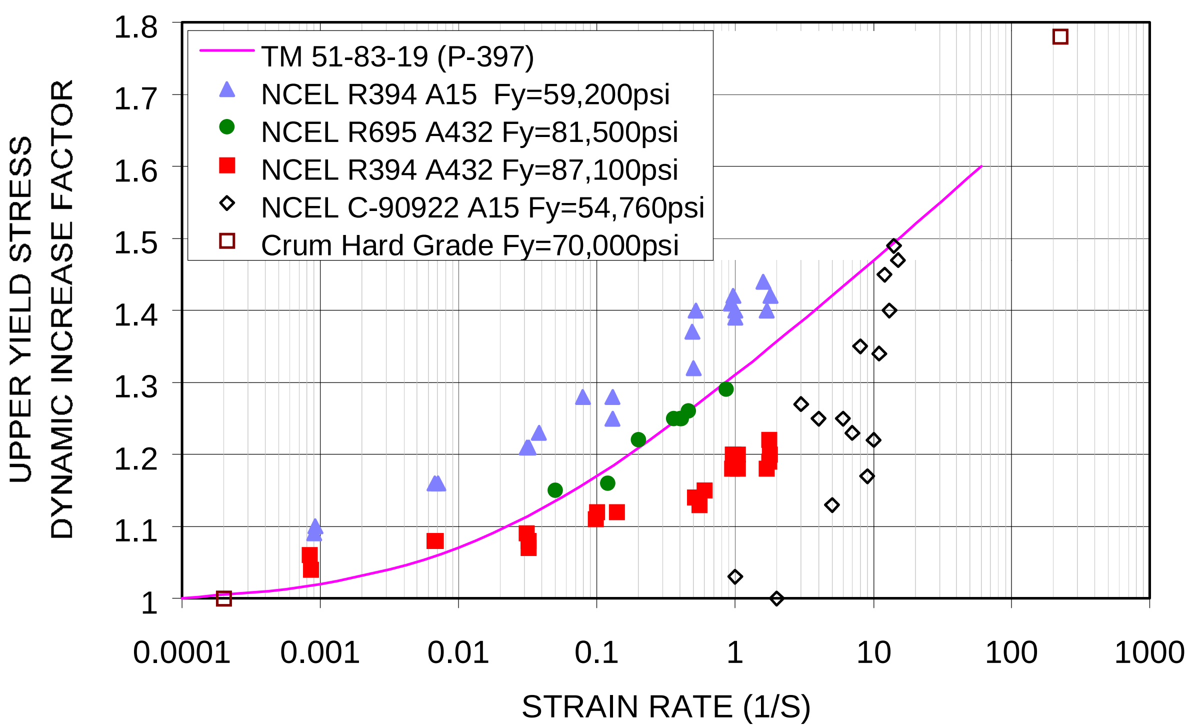

Figure 4. Keenan's design fit compared to additional data [12].
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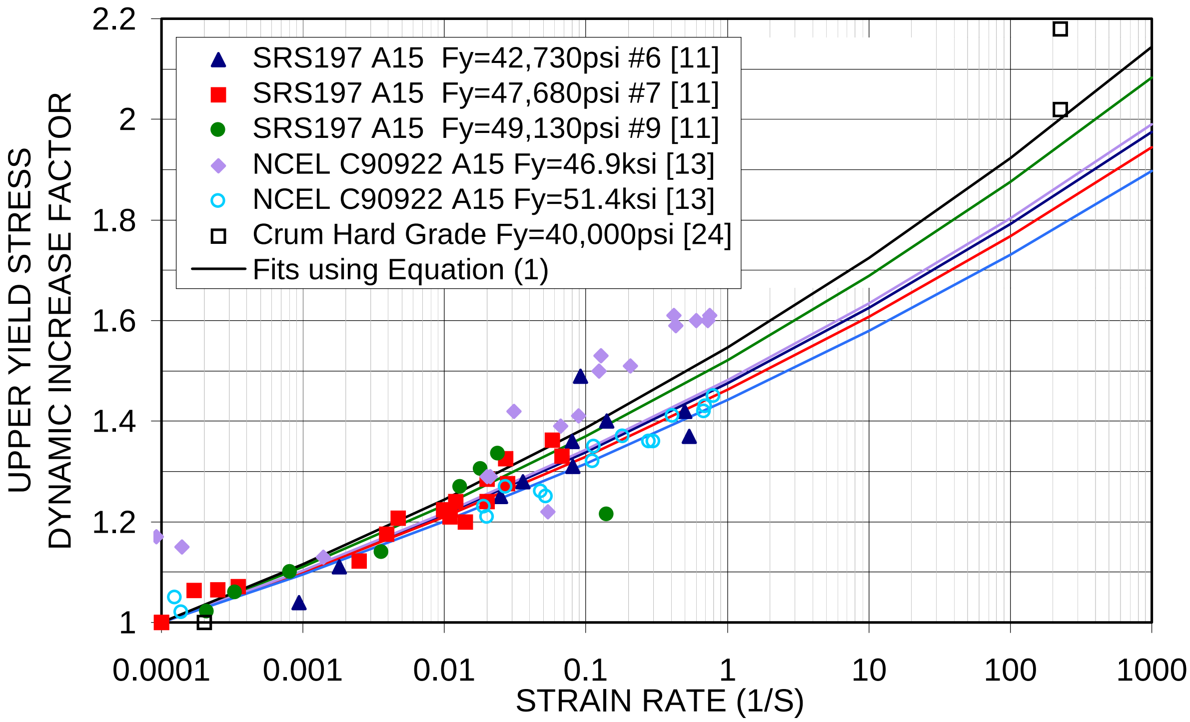

Figure 5. DIF for yield stress for rebars close to ASTM A615 Grade 40.
1 MPa = 145 psi

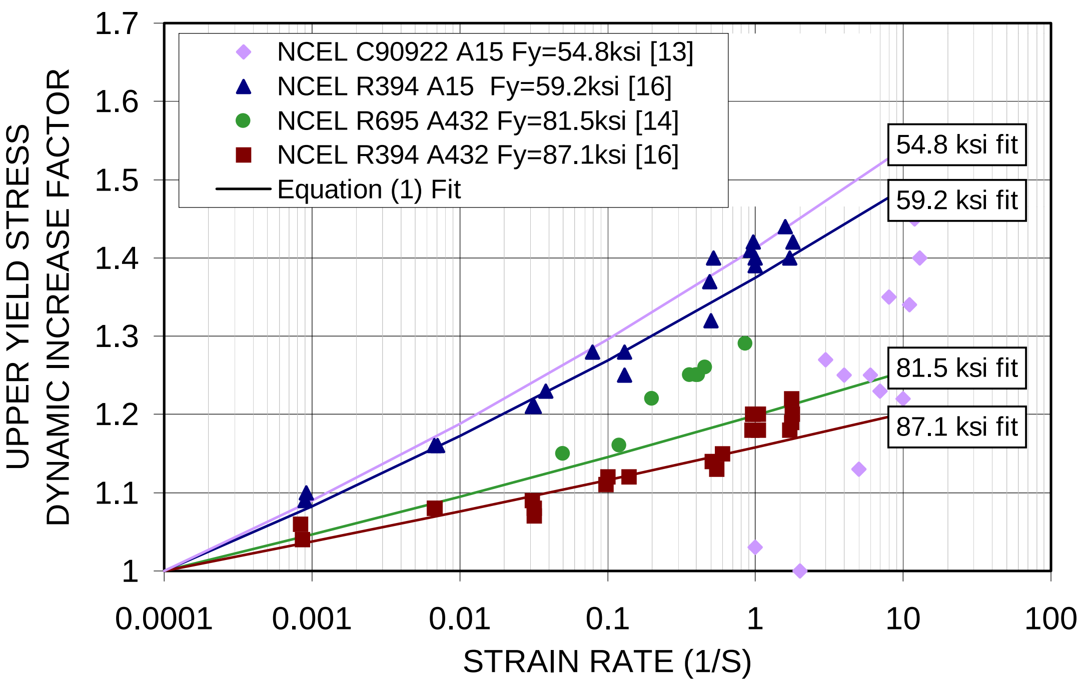

Figure 6. Comparison of proposed fit to data from Figure 4 (yield stress, grade 60).
1 MPa = 145 psi

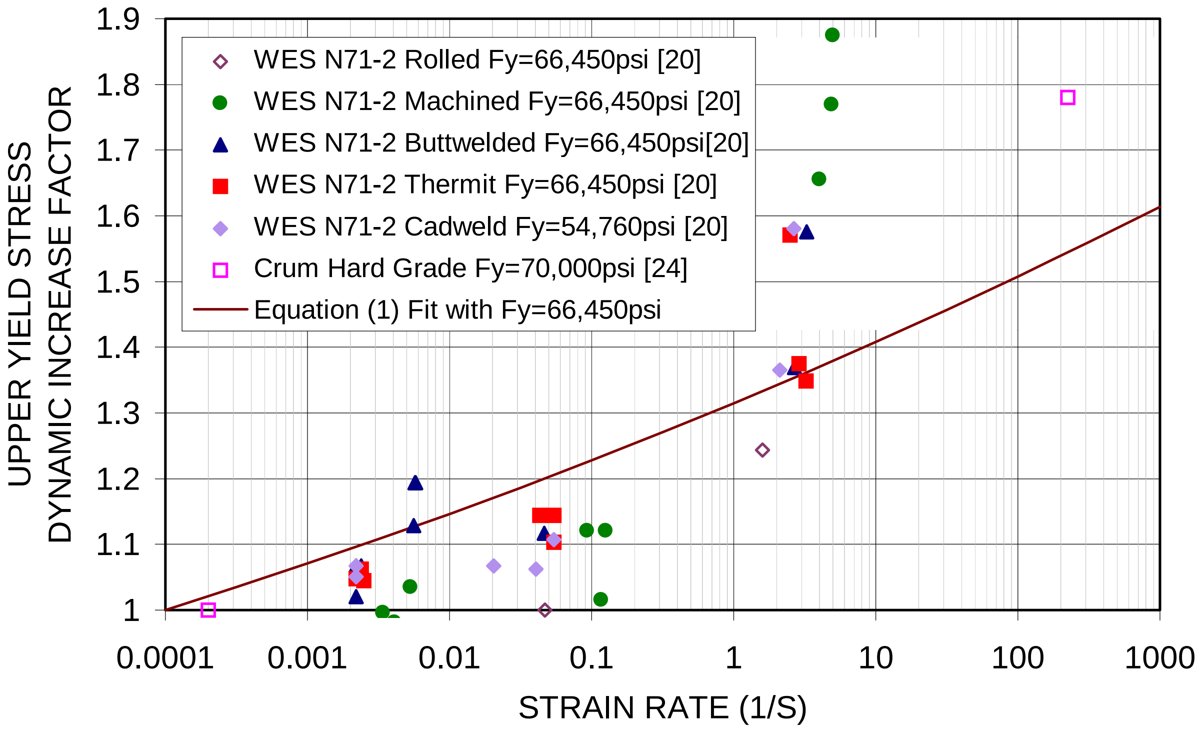

Figure 7. Comparison of proposed fit to Flathau's data [20].
1 MPa = 145 psi

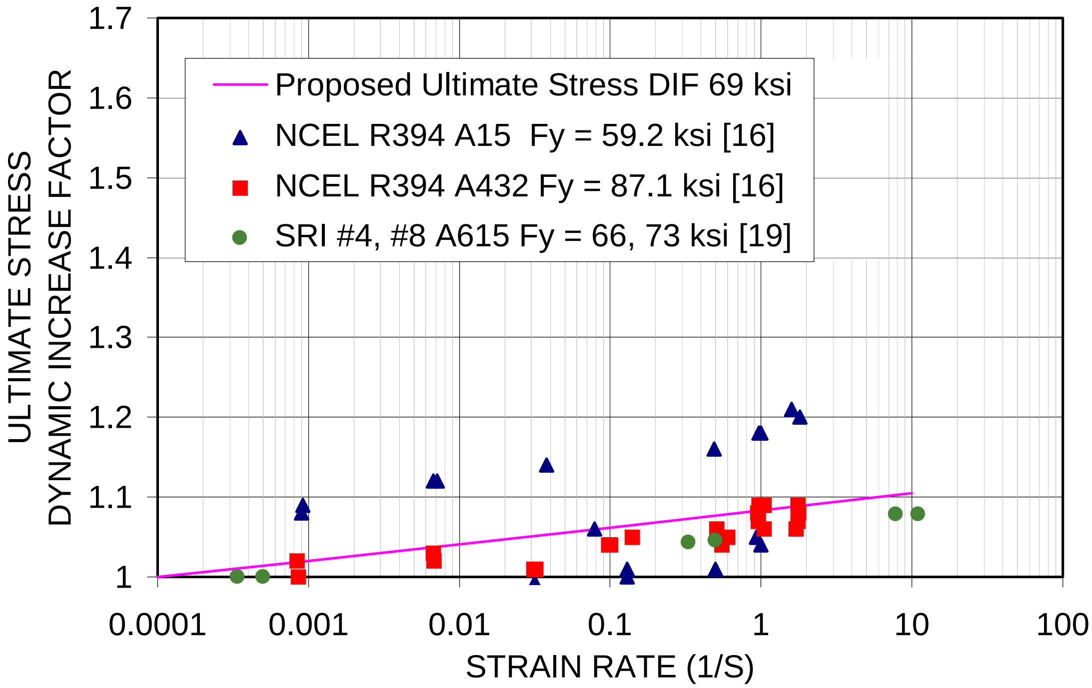

Figure 8. Proposed DIF for ultimate stress of ASTM A615 Grade 60 bars.
1 MPa = 145 psi

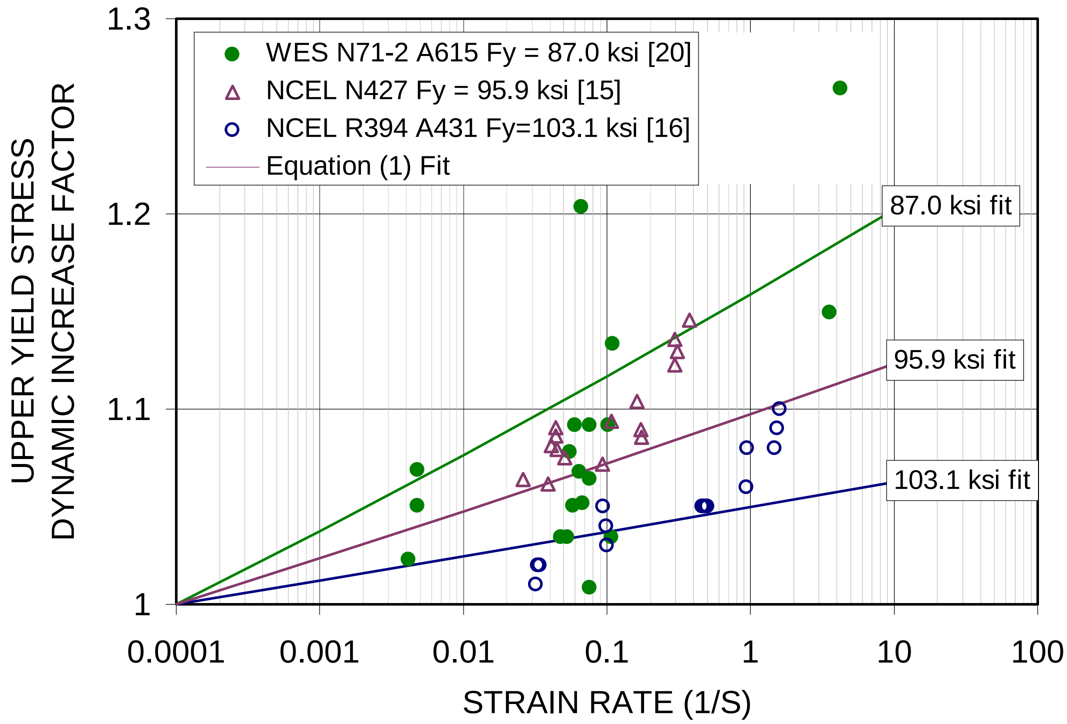

Figure 9. DIF for yield stress for rebars close to ASTM A615 Grade 75.
1 MPa = 145 psi

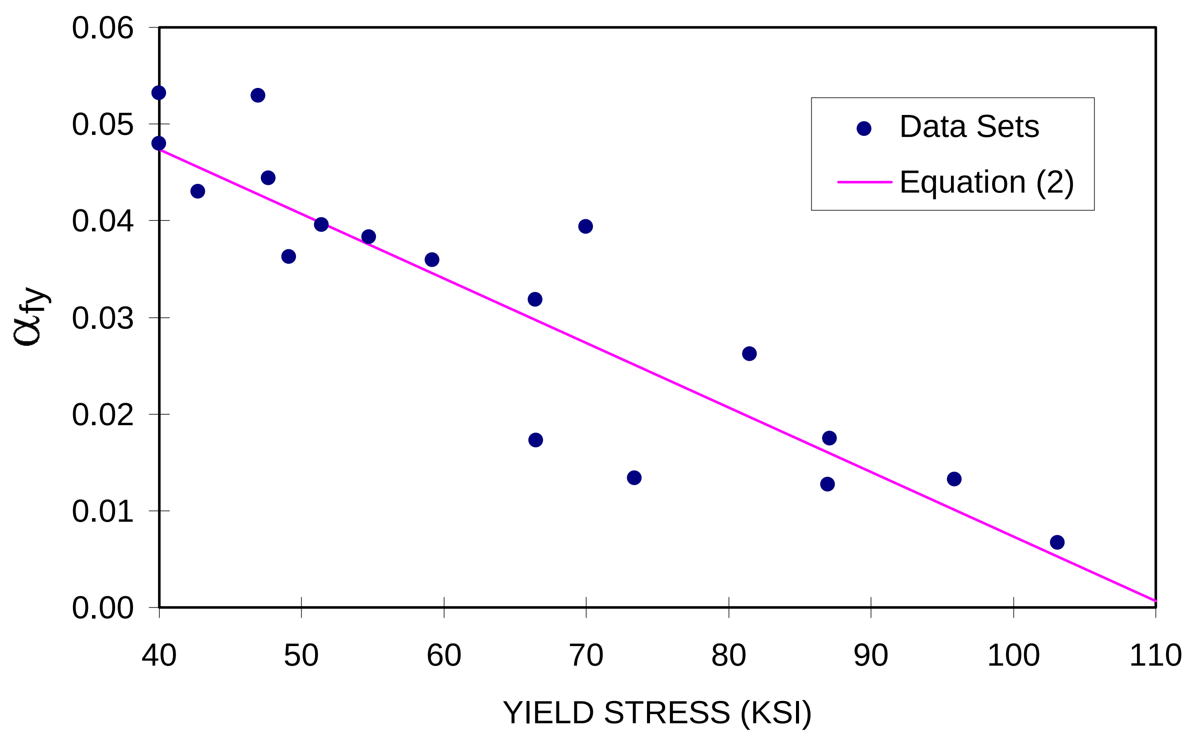

Figure 10. Derivation of equation (2).

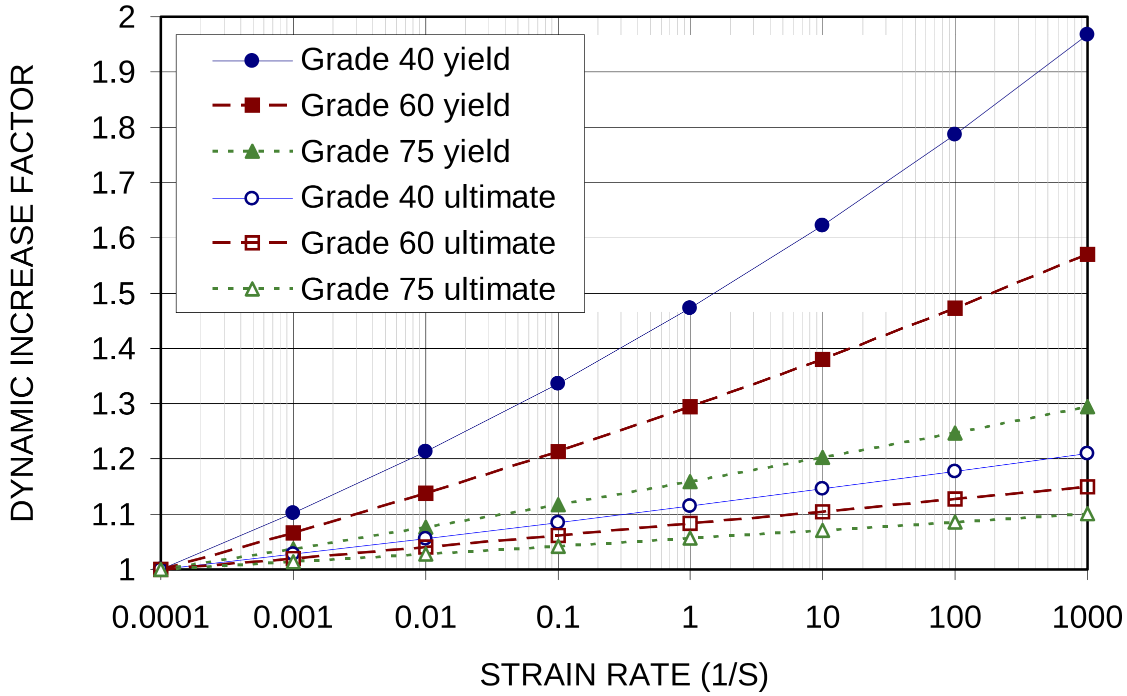

Figure 11. Proposed DIF for ASTM A615 Grade 40, 60 and 75 steel rebar (assuming yield stresses of 48, 69 and 87 ksi, respectively).